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# Complementary Beam-forming

Vahid Tarokh  
Harvard University  
33 Oxford Street Room MD-347  
Cambridge, MA 02139

Yang-Seok Choi and Siavash M. Alamouti  
Vivato Research and Development  
12610 E. Mirabeau Parkway Suite 900  
Spokane, WA 99216

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## Outline

- Motivation
- Smart Antenna Enhancements to IEEE 802.11 Systems
- Problems with Conventional Beam-Forming in CSMA Systems
- Complementary Beam-Forming (CBF)
- Analysis of CBF for Silent and Intended Users
- Examples

## Motivation

- Current IEEE 802.11 wireless LANs support a maximum throughput of 54 Mbps.
- Such a throughput is only achievable in a radius of 4 meters (AT&T-Harvard Measurements and Models)
- At present, a "Wi-Fi revolution" is taking place.
- It is anticipated that the widespread deployment of Wi-Fi will change the entire wireless landscape in few years.

## Motivation

- There will be an abundance of data hungry users in *hot spots*.
- WLAN providers will have to seek devices with increased throughputs and ranges
- This has forced an enormous body of industrial and research activities.

## Smart Antennas Solution

- An enhancement that seems to provide an appealing solution is the use of antenna arrays at access points (AP) in conjunction with beam-forming.
- Such a solution is transparent to receivers and does not force any changes to current standards and receivers.
- In spite of these benefits, design of beam-forming enhancement to WLANs is not as trivial as said above as the combination of beam-forming and the CSMA protocol produces a host of new problems.

## Beam-Forming and CSMA

- Consider a scenario where there are  $m = 2$  transmit antennas and  $k = 1$  intended users.
- Let the channel matrix to the desired user be given by  $(\alpha, \beta)$ .
- A conventional beam-former then induces weights

$$w_1 = \frac{\bar{\alpha}}{|\alpha|^2 + |\beta|^2}$$

$$w_2 = \frac{\bar{\beta}}{|\alpha|^2 + |\beta|^2}$$

at the transmitter.

- If  $c_1$  is the intended transmit signal at time 1 for user 1, then  $w_1 c_1$  and  $w_2 c_1$  are transmitted signals from antennas 1 and 2 respectively.

## Beam-Forming and CSMA

- The intended user receives the signal

$$r_1 = w_1 c_1 + w_2 c_1 + n_1 = \sqrt{|\alpha|^2 + |\beta|^2} c_1 + n_1,$$

where  $n_1$  is the noise.

- The signal to noise power ratio of the desired user improves by a factor of  $10 \log_{10}(\sqrt{|\alpha|^2 + |\beta|^2})$  dB.
- This is not a free gain!

## The Hidden Beam Problem

- Let an unintended user have channel matrix  $(-\bar{\beta}, \bar{\alpha})$ .
- Then the signal at this unintended user is given by

$$y_1 = -\bar{\beta}w_1c_1 + \bar{\alpha}w_2c_1 + \eta_1 = \eta_1,$$

where  $\eta_1$  is the noise vector and the unintended user receives no signal.

- → With conventional beam-forming some users may have low signal components.
- This can cause a problem in a CSMA system.

## The Hidden Beam Problem

- In CSMA, all users and the access point share the same channel for both up-link and down-link transmissions.
- Each user senses the channel and only transmits packets if it determines that the channel is not busy.
- A user with no adequate signal component may wrongly determine that the channel is idle (when busy) and start transmitting packets.
- This may cause unnecessary transmissions, subsequent back-offs, increased network latency and interference.
- Furthermore, the aforementioned undesired packet transmission has an energy penalty which adversely effects the battery life of the remote devices.
- This is called the *Hidden Beam Problem*.

## The Hidden Beam Problem

- In lightly loaded systems (for instance with only one user), the hidden beam problem is not important.
- This “*Hidden Beam Problem*” is further exuberated if the system is more heavily loaded.
- This will be most likely the case both in hot spots or if the system range is increased.

## Complementary Beam-Forming: Idea

- The main intuition behind complementary beam-forming is:  
Detection of busy period is easier than decoding of transmitted packet.
- This is built in the IEEE 802.11 WLAN standards.
- Each device listens to the channel during some time window and compares the energy collected in this window to a CCA (Clear Channel Assessment) threshold.
- Detect activity: if the collected energy  $\geq$  the CCA threshold.
- Thus we will seek to construct a beam pattern which directs most of the transmitted power to the intended recipients while directing a small fraction of the total power to unintended users.

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- Detect activity: if the collected energy  $\geq$  the CCA threshold.
- Our solution (CBF): Construct a beam pattern which directs most of the transmitted power to the intended recipients while directing a small fraction of the total power to unintended users.

## Notation

- For any vector  $X$ , we let  $X^T$  and  $X^H$  respectively denote the transpose and Hermitian of  $X$ .
- For any matrix  $D$ , we let  $W_D$  denote the vector space spanned by the columns of  $D$ .
- Let the channel from transmit antenna  $l$  to the intended user  $j$  be given by  $\alpha_{l,j}$ .
- Let  $A_j$  denote the column vector  $(\alpha_{1,j}, \alpha_{2,j}, \dots, \alpha_{m,j})^T$ . We refer to the vector  $A_j$  as the *spatial signature of user j*.
- Let  $A$  denote the matrix whose  $j$ -th column is  $A_j$ .
- Let  $R^t = (r_1^t, r_2^t, \dots, r_k^t)$  and  $X^t = (x_1^t, x_2^t, \dots, x_m^t)$  respectively denote the vector of received signals at intended users  $j = 1, 2, \dots, k$  and the vector of signals transmitted from

antennas  $1, 2, \dots, m$  at time  $t$ .

- Let  $C^t = (c_1^t, c_2^t, \dots, c_k^t)$ , where  $c_j^t$  is the signal intended to the  $j = 1, 2, \dots, k$  desired user at time  $t$ .
- For any square matrix  $A$ , let  $Tr(A)$  denotes the trace (sum of diagonal elements of  $A$ ).
- Let  $N^t = (n_1^t, n_2^t, \dots, n_m^t)$  be the noise vector components at time  $t$  at the intended users.

## Beam-Forming Matrix

- Then

$$R^t = X^t A + N^t, \quad (1)$$

- Noise components are assumed to be i.i.d. Gaussian.
- *No assumptions* on the statistics of the matrix  $A$ .
- $c_j^t, j = 1, 2, \dots, k, t = 1, 2, \dots, L$  are elements of a signal constellation with average signal  $E[c_j^t] = 0$ .
- The elements of the signal constellation are normalized so that their average power is  $E[|c_j^t|^2] = 1$ .
- In general  $X^t = C^t \mathcal{B}$  where  $\mathcal{B}$  is referred to as the *beam-forming matrix*.

## ZF and Max-SINR Beam-Forming

- Then for a zero-forcing beam-former

$$\mathcal{B} = \frac{(A^H A)^{-1} A^H}{\sqrt{\text{Tr}((A^H A)^{-1})}}$$

and

- We present our technique for the zero-forcing beam-former here. Generalization to the maximum SINR case is obvious.
- We assume that the spatial signature matrix  $A$  is constant during the transmission of a packet.

## Complementary Beam-Forming

- let  $W_A$  denote the vector space spanned by the columns of  $A$ .
- The subspace  $W_A$  is a  $k$ -dimensional subspace of the complex  $m$ -dimensional complex space
- Let  $W_A^\perp$  be the orthogonal complement of  $W_A$ .  $W_A^\perp$  has dimension  $m - k$ .
- Let  $U_0, U_1, \dots, U_{m-k-1}$  form an orthonormal basis for  $W_A^\perp$ . (In other words,  $U_0, U_1, \dots, U_{m-k-1}$  are mutually orthogonal  $m$ -dimensional column vectors of length one in  $W_A^\perp$ ).
- Clearly,  $U_j^H A_i = 0$  for  $0 \leq j \leq m - k - 1$  and  $1 \leq i \leq k$ .

## Complementary Beam-Forming

- The transmitter constructs matrices  $Z_1, Z_2, \dots, Z_L$ , where  $L$  is the length of down-link transmission period, such that:
  - **A:** For all  $1 \leq i \leq L$ , the matrix  $Z_i$  is a  $k \times m$  matrix whose rows are in the set  $\{0, \pm U_0^H, \pm U_1^H, \dots, \pm U_{m-k-1}^H\}$ ,
  - **B:** If  $L$  is even, then  $Z_2 = -Z_1$ ,  
 $Z_4 = -Z_3, \dots, Z_L = -Z_{L-1}$ ,
  - **C:** If  $L$  is odd, then  $Z_2 = -Z_1$ ,  
 $Z_4 = -Z_3, \dots, Z_{L-1} = -Z_{L-2}, Z_L = 0$ , and
  - **D:** Each element  
 $+U_0^H, -U_0^H, +U_1^H, -U_1^H, \dots, +U_{m-k-1}^H, -U_{m-k-1}^H$  appears  $p$  times in the list of  $Lk$  rows of  $Z_1, Z_2, \dots, Z_L$  for some positive integer  $p$ .

## Complementary Beam-Forming

- Once  $Z_1, Z_2, \dots, Z_L$  are constructed, at each time  $t$ , the transmitter chooses the beam-forming matrix

$$S^t = [(A^H A)^{-1} A^H / \sqrt{\text{Tr}((A^H A)^{-1})} + \frac{1}{\sqrt{k}} \epsilon Z_t], \quad (2)$$

where  $\epsilon \geq 0$  is a fixed positive number.

- The choice of  $\epsilon \geq 0$  governs the trade-off between the power pointed to the intended users and that pointed to unintended users.
- For  $\epsilon = 0$ , we recover the conventional beam-forming  $\rightarrow$  Complementary beam-forming generalizes and includes conventional beam-forming as a special case.

## Analysis of CBF

## Intended Users

- **Theorem:** The intended users in complementary beam-forming when compared to the conventional method suffer a loss of at most  $10 \log_{10}(1 + |\epsilon|^2)$ .

## Analysis of CBF

### Silent Users

- **Theorem:** Let  $\lambda_{\min}(A^H A)$  and  $\lambda_{\max}(A^H A)$  respectively denote the minimum and maximum eigenvalues of  $A^H A$ . Then provided that

$$|\epsilon|^2 \leq \frac{(m-k)}{k} \frac{\lambda_{\min}(A^H A)}{\lambda_{\max}(A^H A)}, \quad (3)$$

$$p \geq \frac{m}{k} - 0.5, \quad (4)$$

complementary beam-forming guarantees a fraction  $|\epsilon|^2 \frac{\sum_{j=1}^m |b_j|^2}{m}$  of the transmitted power to an unintended receiver whose spatial signature is  $B = (b_1, b_2, \dots, b_m)$ .

**Comment**

- The condition  $p \geq \frac{m}{k} - 0.5$  means that the transmitted packets must not be too short.

- The condition

$$|\epsilon|^2 \leq \frac{(m-k)}{k} \frac{\lambda_{\min}(A^H A)}{\lambda_{\max}(A^H A)},$$
$$p \geq \frac{m}{k} - 0.5,$$

is a natural one, because when  $\lambda_{\min}(A^H A)/\lambda_{\max}(A^H A)$  is small. Then the matrix  $A^H A$  is close to being singular. This means that even the intended users, do not receive significant signal powers

- In loaded systems, schedulers take care of this issue and choose the users for which the above ratio is larger than a threshold.

## Example

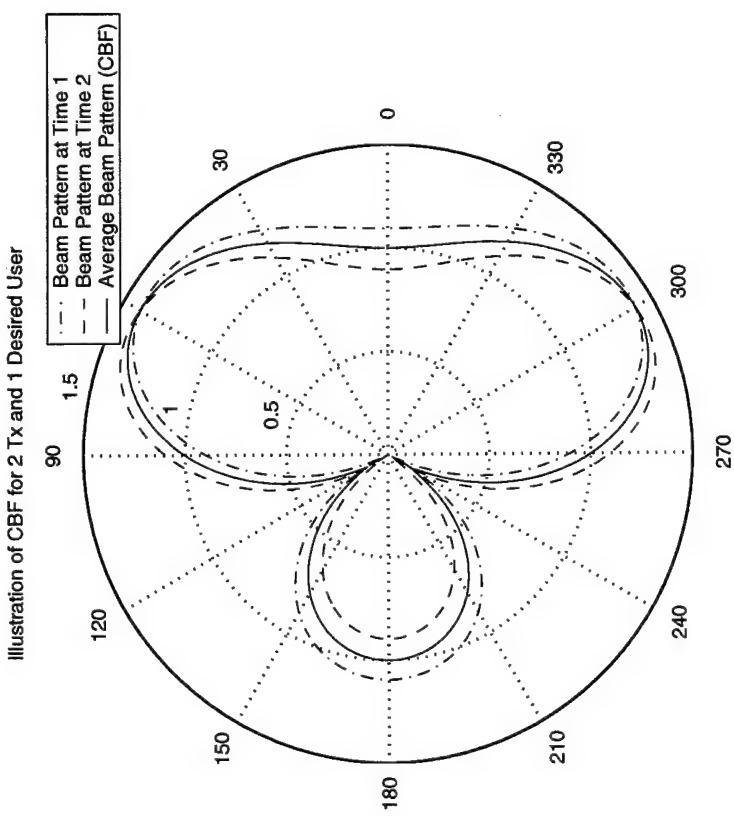
- We consider the case when there are  $m = 2$  transmit antennas and  $k = 1$  intended receivers. Let  $\epsilon = 0.1$ .
- The above Theorems say that power of 20 dB below the transmitted power is guaranteed to silent users. The loss to the intended user is at most 0.044 dB.
- The beam-forming matrices  $S_1$  and  $S_2$  in this case are given by

$$S_1 = \frac{1}{\sqrt{|\alpha|^2 + |\beta^2|}} (\bar{\alpha} - \epsilon\beta, \bar{\beta} + \epsilon\alpha),$$

$$S_2 = \frac{1}{\sqrt{|\alpha|^2 + |\beta^2|}} (\bar{\alpha} + \epsilon\beta, \bar{\beta} - \epsilon\alpha),$$

with  $S_{2L-1} = S_1$  and  $S_{2l} = S_2$  for  $l = 1, 2, \dots, \lfloor \frac{L}{2} \rfloor$ , with  
 $S_L = \frac{1}{\sqrt{|\alpha|^2 + |\beta^2|}} (\bar{\alpha}, \bar{\beta})$  when  $L$  is odd.

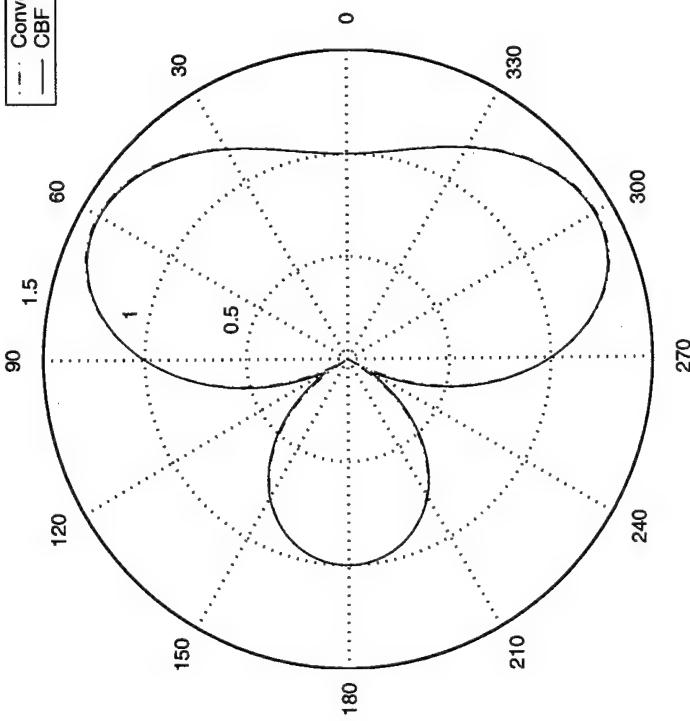
## Time Domain CBF



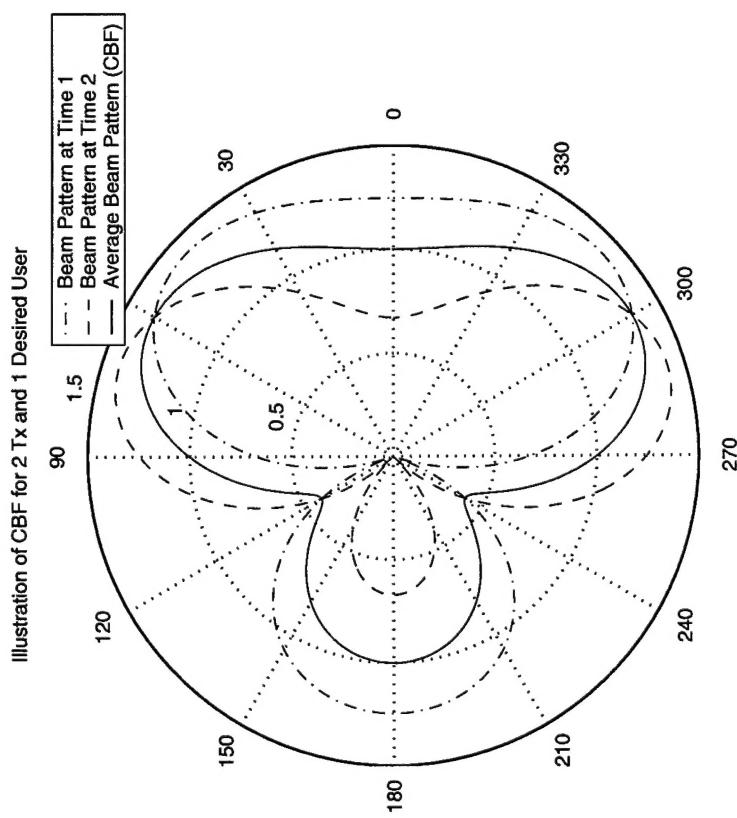
## Time Domain CBF

Comparison of CBF With Conventional Beam-forming, 2 Tx, 1 Desired User

Conventional  
— CBF

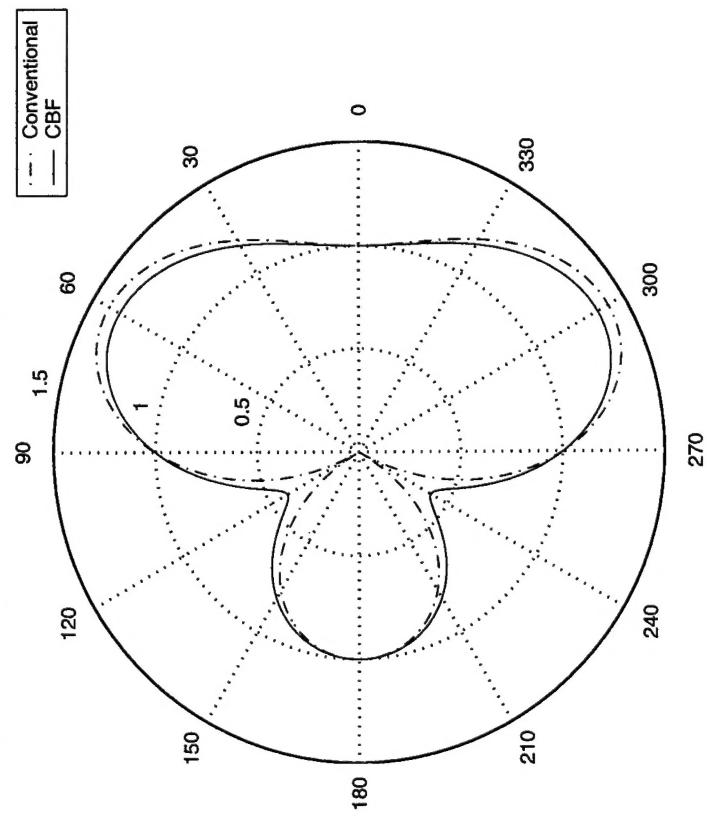


## Time Domain CBF



## Time Domain CBF

Comparison of CBF With Conventional Beam-forming, 2 Tx, 1 Desired User



## Other Issues

- Analysis show that the complexity of complementary beam-forming is approximately twice as much as that of the conventional beam-forming.
- It has been observed via simulations that using complementary beam-forming significantly enhance the performance of a heavily loaded smart antenna enhanced IEEE 802.11 system as compared to the case when conventional beam-forming is employed.

## **Conclusions**

- Smart antennas are an appealing solution for increasing the range and throughput of IEEE 802.11 systems because they are backward compatible.
- Combining smart antennas and CSMA produce a host of new challenges.
- An example of these problems is the hidden beam problem.
- We proposed complementary beam-forming to address this problem.